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Ames Research Center

"Generation of a Monodispersed Aerosol"

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I. INTRODUCTION

Laser velocimetry requires that light be scattered by small particles passing through an interference fringe pattern generated by crossing coherent laser beams. When subsonic velocity measurements are to be made, the spacing between these fringes is on the order of several microns; the particles must, therefore, be smaller than this spacing so as to insure a good modulated signal at the photodetector. In addition, the particles must have a low enough specific gravity to allow them to follow turbulent fluctuations of the fluid.

A. PROJECT OBJECTIVES

To identify and laboratory test methods for the generation of a monodispersed aerosol subject to the parameters and constraints given below.

B. AEROSOL PARAMETERS

1. Size Distribution: Usually it is not possible to produce particles all having a common diameter. Therefore, for any method which is deemed to have some promise, the size distribution of the aerosol must be specified through measurement (either direct or indirect). Some consideration should be given to whether or not the nominal particle size can be selectively controlled by the operator of the aerosol generator. The particle diameters should not be greater than 10 microns nor smaller than 1 micron.
2. Specific Gravity: While dense smaller particles are acceptable, those having the lowest specific gravity are the most desirable. Typical particles which have heretofore been used range in density from polystyrene latex with a specific gravity of 1.05, to aluminum oxide with a value near 6.0.

3. Scattering properties: When the particles pass through the laser light, they scatter light in all directions. It is desirable in current laser velocimeter applications to have a high scattering cross-section for the backscattered radiation. For any of the proposed materials, the angular distribution of the scattered light should be measured so that the materials may be evaluated on a relative basis. The laser wavelengths of interest are 0.4880 and 0.5145 microns, although the above measurements can be made at 0.6328 microns as long as the material has essentially the same characteristics at wavelengths near 0.5 microns.

4. Cost: Since a significant amount of the aerosol may at times be used, consideration should be given to the cost of the proposed material.

5. Production: The production of the aerosol can be from a chemical reaction, vaporization by heating or combustion, or any other reasonable method which is safe.

C. CONSTRAINTS

1. The aerosol must be non-toxic.
2. The aerosol must not have corrosive properties.
3. If possible, the aerosol might even eventually evaporate from the surfaces upon which it becomes deposited.

D. EXPECTED RESULTS

1. Literature survey report on aerosol generator art.
2. Preliminary testing of aerosols for laser Doppler velocimetry applications.
3. Proposal for the design and construction of aerosol generator(s) as a result of the literature survey and of the preliminary testing of particles.

E. PROCEDURE

1. Information collection from the literature, from commercially available products, and from experts working the field. The following basic topics were investigated:

Aerosols
Air Pollution -- analysis
Atomizers
Dispersion
Particles -- optics
-- size analysis
Smoke -- generators
-- density measurements
Sprays
Wind Tunnels -- visualization

2. Experimental capability: The development and procurement of test methods and equipment.

3. Summary of results, proposal for future work.

II. LITERATURE SURVEY SUMMARY

A. INTRODUCTION

The operation of a laser anemometer depends fundamentally upon the availability of particles to scatter light into a photodetector. The optical arrangement and measurement precision are dependent of the size distribution and concentration of the particles. The signal quality depends upon laser power and the ratio of fringe spacing to particle diameter. Also very important is the fact that the physical characteristics of the particle dictate the extent to which its velocity and trajectory characterizes the fluid flow. Therefore, a knowledge of the physical properties of light-scattering particles is necessary to the successful operation of a laser anemometer.

Davies (10) conducted a literature review on particle size analysis techniques. Most of the references cited were of a highly specialized technique for very specific applications, or the sources were foreign publications not available to us. Melling and Whitelaw (32) outline the criteria which limit the particle characteristics together with their

implications for practical anemometry in gases. In addition, they describe means of generating particles which conform to these limits and available methods for testing that they have been achieved.

B. PARTICLE TECHNOLOGY

1. Limits Imposed on Physical Properties of Particles by Aerosol Dynamics

The specification of limits on the physical properties of particles is generally based on the ability of the suspended particles to follow turbulent fluctuations in the flow to a prescribed upper frequency within a certain accuracy limit. Melling and Whitelaw (32) base their analysis of the motion of a spherical particle in a moving fluid on Basset's (2) expression for the balance between acceleration forces on a sphere and a stationary displaced fluid as follows:

$$\frac{\pi d_p^3}{6}\rho_p\frac{dU_p}{dt} = \frac{\pi d_p^3}{6}\rho f\frac{dU_f}{dt} - \frac{1}{2}\frac{\pi d_p^3}{6}\rho_f\frac{dV}{dt} - 3\pi\nu\rho_f d_p V$$
$$- \frac{3}{2}d_p^2\,\rho_f\sqrt{\pi\nu}\int_{t_o}^{t}\frac{dV}{d\xi}\frac{d\xi}{\sqrt{t-\xi}} \qquad (1)$$

where

d_p is the particle diameter

ρ_p, ρ_f are the densities of the particle and fluid respectively,

ν is the kinematic viscosity of the fluid,

V is the difference between the particle and fluid velocities,

i.e., $U_p - U_f$

and

t is time.

The four terms on the right-hand side of equation (1) represents, respectively, the acceleration of the fluid, the resistance of an inviscid fluid to the accelerating sphere, the Stokes drag force and a drag force which takes account of the unsteady motion of the sphere. The equation may be applied to a turbulent low on the assumption that:

a) The turbulence is homogeneous and statistically stead .
b) the particles are much smaller than the turbulence microscale,
c) Stokes drag law applies to the relative motion of the particle and the fluid, and
d) there is no interaction between particles.

Melling and Whitelaw further observe that Laser Doppler Measurements of fluid flow through rotating machinery introduce the question of particle motion in centrifugal fields. They refer to Burson, et. al. (6) who showed that near micron solid particles injected near the center of a forced vortex air flow move nearly radially, i.e., they represent accurately the tangential velocity of the air. The radial velocity of the particle following Stokes drag law can be calculated from the simple equation:

$$V_r = \frac{r\omega^2}{a} \tag{2}$$

where r is the distance of the particle from the axis of the field rotating at angular velocity ω, and $a = 18\mu/d_p^2\rho_p$. This equation assumes equal tangential velocities of particle and fluid, zero radial fluid velocity, and solid body rotation. The ratio of the radial velocity component to the tangential component $V_r = r\omega$ is then:

$$\frac{V_r}{V_t} = \frac{\omega}{a} \tag{3}$$

for a 1μ water droplet in a vortex of air rotating at 9000 rpm, $\frac{V_r}{V_t}$ is less than 0.003. Indeed, the trajectories of small diameter, low density particles closely approach the trajectory of the fluid.

The lower limits of particle density and diameter are compartively unimportant. Fluid densities are always smaller than particle densities and the intensity of light scattered by small particles is disproportionately low. Edwards, et. al., (13) have quantified the extent to which Brownian motion may contribute to the broadening of a laminar-flow Doppler spectrum. Their method shows that, for a measuring volume of diameter 0.25 mm and a beam intersection angle of 14°, diffusion broadening is comparable with transit-time broadening for velocities less than 8 mm/s when using 1μ particles in air at normal conditions or less than 80 mm/s with 0.1μ particles. The velocity deduced from the spectrum is obviously unaffected by Brownian motion.

2. Mathematical Treatment of Particle Characteristics

Katz and Shinnar (26) give a stochastic approach to particulate processing systems which can give the investigator insight to the underlying mechanism and to the nature of the observed fluctuations in particle size and number. O'Connell and Prausnitz (37) describe the applications of statistical mechanics to the equilibrium configurational properties of fluids and fluid mixtures. Houghton (21) describes particle and fluid diffusion in homogeneous fluidization:

> "A Markoff theory of particle diffusion in homogeneous fluidization is founded on nonlinear Langevin equations and associated quasi-linear and linear stochastic equations describing the 'microscopic' particle-fluid and particle-particle interactions when velocity fluctuations are small and their distribution is Gaussian. Anisotropy is permitted through directional differences in fluctuation energy and particle-fluid friction. Particle and interstitial fluid diffusion are found to be symmetric stochastic processes characterized by a single directional diffusivity sensitive to void fraction and particle-fluid properties. Comparisons of theoretical and experimental diffusivities indicate that considerable anisotropy and inhomogeneity exist during fluidization, attributable to mean velocity distributions and random 'macroscopic' disturbances. The stochastic model is then generalized to include fluidized diffusion arising from macroscopic turbulence on the scale of several particle diameters."

Subsequent to generating aerosol particles, techniques must be found which will examine the various particle properties. The following sections are devoted to summarizing the techniques which are found as a result of the literature survey.

3. Particle Size Measurement

The simplest method for particle size measurement for our project is size estimation from the Doppler Signal. Melling and Whitelaw refer to ideas proposed by Durst (11) indicating that Doppler signals of high quality, i.e., having a large Doppler frequency modulation relative to the peak amplitude, will be obtained with particles of diameter close to the fringe spacing, where the fringe spacing ΔX is given by:

$$\Delta X = \frac{\lambda}{2 \sin \phi} \tag{4}$$

for light beams of wavelength λ intersecting at an angle 2ϕ.

Melling and Whitelaw also indicate that typically ΔX is arranged to be near 2μ, and so the particles giving a good signal will respond to turbulent fluctuations up to a fairly high frequency. Large particles with small Doppler modulation may not follow the flow, but need not distort the turbulence statistics unduly, since their contribution to the Doppler signal is comparatively small and could be further reduced by amplitude discrimination of the high pass-filtered signal.

Proctor (40) describes the use of the continuous-wave He-Ne laser to measure the surface area of small concentration (<3000 particles per cm^3) of dust particles, of size less than 5μ, suspended in air. The suspension is passed through a size-selector to remove dust particles greater than 5μ in size and then into a chamber between one of the laser mirrors and the end of the laser tube. (See Figures 1 and 2) Scattering and absorption of radiation from the cavity by the dust particles causes a change in the amount of radiation reflected back into the laser tube, which in turn produces a reduction in the intensity of the output beam. The relationship between the

surface-area concentration in the output intensity is derived, and experiments with an instrument of this type are described and discussed as well.

Hinds and Reist (19) present the basic theory, experimental techniques and results describing a technique for sizing aerosol particles in situ using laser Doppler spectroscopy. Unlike conventional light scattering procedures which use average intensity information, this technique utilizes the Doppler spectroscopy. Unlike conventional light scattering procedures which use average intensity information, this technique utilizes the Doppler shifted frequency of the scattered light produced by the Brownian motion of the aerosol particles to determine particle diffusion coefficients and size. Experiments were carried out using monodisperse dibutylpthalate aerosols and monodisperse polystyrene latex spheres, in concentrations ranging from 10^3 to 10^6 particles per cm^3. Measured particle sizes were within 10% of the size predicted by conventional light scattering methods for the DBP particles and the reported sizes of the PSL particles. Based on these results it is concluded that laser Doppler spectroscopy can be utilized to accurately measure aerosol particle size in situ.

In a second article Hinds and Reist (20) present the theoretical basis and the results of a computer simulation which described the operational limits of size and concentration for aerosol sizing by laser Doppler spectroscopy.

Schleusener (43) developed a technique of automatic high speed particle sizing by using a visible He-Ne gas laser cavity beam as the sizing instrument and a multichannel pulse height analyzer to store and present visual size frequency distribution information in real time. Particle sizing rates as high as 10,000/sec are attainable in size ranges from about 1 to 300μ. Westwater and Cohen (52) applied the Bachus-Gilbert Inversion technique to the determination of aerosol size distributions from optical scattering measurements.

Pavitt, et. al. (38) tested the feasibility of measuring the size distribution of cloud particles from an aircraft with a holographic technique. The water droplet size ranged from 15 to 100μ. Various factors

affecting the resolution and the depth of the sample volume obtainable with this technique are considered and it is shown that the spatial coherence of the pulsed laser is likely to be the most serious limitation.

Fourney, et. al. (14) designed an experimental technique for obtaining the spatial size and velocity distribution for liquid or solid aerosols suspended in air flow. This technique leaves the flow undisturbed and allows for a large range of particle sizes and velocities. The successful combination of a Q-spoiled ruby laser and holography was employed to record the desired information. A He-Ne laser was used to reconstruct the magnified image which as analyzed using closed circuit television.

A ballistic particle size separator which operates on an aerodynamic principle and effects ordered size separation of both liquid and solid particles was developed by McGinn and MacWalters (30). For this separator an approximate size-range relationship for spherical particles is dervied. The resulting calculations of the spatial separation as a function of size for spherical particles of unit density are in accord with preliminary experimental data for diameters between 10 and 100μ.

Specifically applicable to solid particle sizing are the following methods. Schleusener and Reed (44) apply turbidimetry to layered sedimentation and give both a theoretical treatment and experimental investigation results. Carroll and Abst (6) developed a sieving method for particle size distributions from less than 44 through 1μ. Moroz, et. al. (33) investigate a portable dust particle counting and size analyzing instrument with immediate readout which would enable number vs. size distributions of airborne particulate matter to be made known quickly in locations difficult of access, such as underground mines.

Kotrappa and Light (27) investigate in some detail the design and performance of the Lovelace Aerosol Particle Separator. They describe the separator as follows (see Figure 3 for a schematic of the separator):

> "The Lovelace aerosol particle separator (LAPS) provides a continuous separation of aerosol particles in the micron and submicron size ranges according to their aerodynamic equivalent diameters. This new device uses the principle

of centrifugal separation of particles in a spinning spiral duct. The LAPS is essentially a spinning rotor driven by a motor at a desired constant speed. An aerosol sample is drawn into an expanding spiral duct through an inlet at the axis of the rotor and is entrained in a laminar stream of clean air and drawn by negative pressure through the channel. The particles are deposited according to their aerosynamic diameters along a 46.2 cm long collection foil lining the outer wall of the spiral duct and the very small particles on a filter at the exit end of the spiral, thereby providing a continuous separation of aerosol particles in the entire size range of interest. The device is relatively inexpensive, rugged, easy to operate, and can be driven either by an induction-type household motor or by a more elaborate centrifuge drive. It is suitable for separating aerosol particles for a variety of purposes including analysis of aerodynamic particle size distribution, preparation of monodisperse particles, measurement of densities of spherical aerosol particles, and measurement of particle shape factors. Because the entrifugal forces are directed toward the collection foil and cause the collected particles to be held firmly in place, the instrument can be used to collect large samples without significant change in calibration or resolution characteristics."

4. Measurement Techniques For Other Particle Properties

This section summarizes references on measurement techniques for particle properties (such as optical vs. physical properties, particle mass, charge analysis, coagulation properties, feasibility of fluidization, and scattering characteristics) which may be of interest in future experimental work on the project once the basic research on particle sizing and light-scattering characteristics has been completed.

Vogel, et. al. (50) describe the experimental arrangement for the comparison of the optical and physical characteristics of particulate smokes. Their smoke consisted on zinc oxide or magnesium oxide crystals suspended in an inert gas such as nitrogen. Isaken, et. al. (23) describe the application of low angle light scattering from a laser source to the measurement of the state of agglomeration of dispersed systems. Berg. et. al. (3) describe a charge analyzer that permits rapid charge analysis of aerosols and sprays emerging from a nozzle at a high flow velocity. Chuan (7) describes an active impactor which measures directly the mass of

airborne particulates impinging upon it, producing, in real time, data on total particulate mass concentration and particle mass distriubtion.

Walter (51) has set up a coagulation equation and has proposed a numerical solution for calculating the changes with time of concentration and size distribution of condensation aerosols which are formed in the atmosphere, or in the laboratory, by the continuous production of primary particles, either by spontaneous condensation or gas reactions. Using the equation, the change of concentration with time is calculated when there is a constant rate of production of primary particles of uniform size. Finally, the change with time of the corresponding distribution of particle size of the condensation aerosol is examined and the influence upon it of previously existing large particles is shown.

Baerns (1) investigated the feasibility of gaseous fluidization of particles in the size range of less than 50 microns. The ratio of the incipient fluidization velocity, calculated by a conventional relationship without accounting for interparticle forces, to the incipient fluidization velocity, determined by pressure drop and heat transfer measurement, was used as an index, FI, describing the fluidizability of a particulate material. The results indicate that FI is closely related to the interparticle adhesive force. The limitations of the feasibility of fluidization depend on the ratio of the weight of a particle to the sum of its weight and adhesive force; no fluidization could be obtained when this ratio was less then 10^{-3}.

5. Additonal References

This section summarizes references which are of a more general nature and very important to our project but have not been discussed in the previous sections.

Of particular interest to our project is the book by Green and Lane PARTICULATE CLOUDS: DUSTS, SMOKES AND MISTS (Second edition, Princeton N.J.: Van Nostrand 1964). The operating principle of various common generation techniques of aerosols are described, both theoretically and in reference

to experimental results. Several chapters are devoted to the following topics: physical characteristics and optical properties of aerosols, coagulation, deposition and filtration, and sampling and estimation techniques. This book is excellent for a fundamental understanding of particulate smokes and generation techniques.

ATMOSPHERIC AND SOURCE SAMPLING published by the U. S. Department of HEW (17) gives brief description of properties of aerosols. Of particular interest is a table giving the size range of contaminants naturally occuring in the air. (See Table 1.)

Friedlander (15) considers the characterization of aerosols distributed with respect to size and chemical composition and gives a description of the classification and design of aerosol measuring devices. Fuchs (16) issues a warning on latex aerosols. Briefly, he writes that in spite of the high monodispersity of Dow Latices, the monodisperisty of aerosols generated by atomizing latex suspensions may be impaired by formation of particle aggregates and by the effect arising from the presence of latex stabilizer: formation of "empty" particles and of shells on polystyrene particles. These effects may distort considerably the calibration of various aerosol instruments. They can be eliminated only by extreme dilution of latices.

C. AEROSOL GENERATION TECHNIQUES

There exist several basic aerosol generation techniques, some more applicable to laser Doppler velocimetry (LDV) than others. This section is divided into four major categories: 1) Atomization (air - jet - blast, spinning disc, ultrasonics), 2) Chemical Process and Combustion, 3) Condensation and Nebulization, and 4) Specialized Techniques for limited application but which may be of interest to later phases of this project.

Green and Lane give a very comprehensive overview of generation techniques explaining both the particle theory involved and the experimental work done by various groups as verification of the theory. One of the first and most famous aerosol generators builts is that one developed by Sinclair and La Mer in 1949. They were the first to prepare monodispered aerosols,

in which the sizes of the particles lie within ± 10% of the mean value, by carefully regulating the condensation of vapour upon suitable nuclei. Figure 4 illustrates a generator of this type. Green and Lane give the following description of the generator.

> "The substance from which the aerosol is formed is vaporized by heating it electrically in a glass boiler A to 100-200°C, depending upon the boiling point of the substance and the particle size described. Dry air or nitrogen, freed from foreign nuclei, is passed ove r or bubbled through the liquid (or molted substance) and mixed with a strea, of condensation nuclei produced in B. The mixture of gas, vapor and nuclei passes through two small jets into the reheater flask C, which is heated electrically to about 300°C, where any residual spray is vaporized and the nuclei are well mixed with the vapor. It then passes up a long double-walled chimney, in which it is slowly and uniformly cooled, becoming supersaturated and condensing uniformly upon the nuclei to form fine aerosol particles. The boiler and reheater flasks are enclosed in an insulated electrically heated box equipped with thermostatic regulators, in order to minimize temperature fluctuations which tend to destroy the uniformity of particle size of the aerosol."

Recently Edwards and Brinkworth (12) developed a device for the control of particle size in the La Mer aerosol generator. This device provides automatic long-term control of the particle size. The control system input signal is derived from the light-scattering properties of the outgoing particles. Over periods of eight hours, variation in mean size are found to be typically less than 10% for aerosols with particle diameters of about 1μ.

1. Atomization

a. Air (Jet) Blast

This section describes various atomization, or dispersion, techniques for aerosol generation. Dispersion methods involve the subdivision of a coarse system into particles attaining or approaching colloidal dimensions. Energy is imparted to a liquid causing it to assume an unstable configuration and disintegrate into droplets, or is applied to disrupt or disperse a solid substance into fine particles. The former process has been studied intensively in connection with the design and operation of atomizers widely

used in industry and technology. Yet knowledge of the basic physics of the shatter process itself is still incomplete and the mechanism of aerosol generation by liquid atomization cannot always be analyzed quantitatively although in recent years more study has been devoted to the development of particulate matter theory.

Green and Lane give the following brief description of the various basic methods of atomization.

> "Atomizing devices commonly used in generating aerosols may be classified in three main types. The first type is the air-blast or aerodynamical atomizer in which compressed air or other gas is used at high velocity to break up liquid emerging from a nozzle, and plays a predominating part in achieving a fine degree of atomization. This kind of break-up is met in the conventional paint spray gun, in venturi atomizers and in many atomizers which generate aerosols for insecticidal, disinfectant and therapeutic purposes. It is characteristic of atomizers of this type that they give a very wide range of droplets within the atomizer."
>
> "The second type depends on centrifugal action, the liquid being fed on to the centre of a rotating disc, cone or top and centrifuged off eht edge. The spray is characterized by uniformity of the main droplet size, in marked contrast to the heterogeneity of sprays produced by other methods."
>
> "Thirdly there is the hydraulic or hydrodynamical type, in which liquid is forced through a nozzle and breaks up into droplets. Here the disintegration depends more upon the physical properties of the liquid and the conditions of ejection from the nozzle than upon interaction between the liquid and the surrounding gas. Probably the most successful hydraulic atomizer, and indeed the only one which has application for fine atomization, is the swirl chamber atomizer used in agricultural spraying equipment, oil-fired furances, internal combustion engines and gas turbines. The swirl is produced by leading the liquid tangentially into the chamber and allowing it to spray out through a central orifice of small diameter.
>
> "Outside this classification, and very much less well-known are two additional types which we may list as special atomizers. These are the electrostatic atomizer which breaks up liquid by the action of electrostatic forces and the acoustic atomizer which utilizes high intensity sonic or ultrasonic vibrations."

Melling and Whitelaw (32) indicate that their research at Imperial College has led to a preference for atomization and fluidization techniques over chemical reaction and combustion for use in laser anemometry since the former can be more easily and precisely controlled. Of interest is their table of aerosols used in laser Doppler Anemometry. (See Table 2.)

Melling and Whitelaw also strongly recommend the twin-fluid atomizer for the seeding of cold air flows. This type of generator is of great interest for our project work for finding a generation technique for the #5 wt mineral oil. They describe the generator as follows.

> "Air-blast (or twin-fluid) atomizers are most suited to laser anemometry since they can produce much smaller droplets than the other designs and, at low flow rates, diameters down to about 1 μm can be obtained. They use a jet of air to break up a liquid film and Figure 5 shows a glass atomizer of this design. Liquid from the reservoir is drawn up the tube A by the injector effect of the air jet from tube B; as it emerges from tube A, the shearing effect of the air jet breaks the liquid film into a fine spray. Larger droplets tend to strike the sides of the atomizer and drain back into the reservoir while the smaller drops follow the flow of air. Atomizers of this type have been successfully used at Imperial College with flow rates of approximately 10 l/min and a seeding concentration of about 10^{10} particles per m^3 at an inlet pressure of 1.4×10^5 N/m^2, using silicone fluid of kinetic viscosity 500 centistoke (5×10^{-4} m^2/s). Orifice diameters of approximately 0.5 mm were used in the design and optimum performance was found to depend critically on the relative positions of the tips of the two tubes. For example, a batch of six atomizers gave flow rates between 7.2 and 13.3 l/min. To overcome this difficulty, the brass atomizer shown in Figure 6 was designed. In this case, oil is forced under pressure into the narrow annular gap, G, and is atomized by the central air jet. A flow of about 3.5 l/min is obtained from this design with the same back pressure on the atomizer of Figure 5 but, in this case, the rate is proportional to the pressure to the pressure of the air-jet supply and control of particle size and concentration may be achieved by adjusting the gap width by the screw mechanism shown.
>
> "Twin-fluid atomizers produce a steady flow or aerosol and require little attention. The mean diameter of the aerosols produced by the designs shown on Figures 5 and 6 is of the order of 1-3 μm. Atomizers of this type are strongly recommended for the seeding of cold air flows.

"Pressure and rotating-disc atomizers are less suitable for laser anemometry because the mean diameter of the aerosols they produce are substantially larger than required. The former achieves liquid break-up by forcing the liquid through an orifice from which it emerges as a fan-shaped conical film prior to collapse; in the latter, a thin liquid sheet flows radially across a disc and disintegrates at the edge to produce droplets of diameter d_p where

$$d_p \propto \frac{1}{\omega} \frac{\sigma}{\rho d}^{1/2} \tag{5}$$

from a liquid of surface tension σ and density ρ on a disc of diameter d rotating at speed ω. Both arrangements permit the dispersal of large mass flows of liquid but with an unsuitable droplet diameter. Mechanical separation of the large droplets from the small is often possible by means of the different trajectories of the large and small droplets. The process is, however, inefficient and inconvenient."

b. Spinning Disc

Green and Lane give a good introduction to the basics of the spinning disc method of generating aerosols:

"In contrast to other methods of atomization, which invariably give widely heterogeneous mists, the spinning disc gives a spray of nearly uniform drop size provided that the rate of feed of liquid on to the center of the disc is dept low; at higher rates of flow inertial forces become important and the liquid then leaves the edge of the disc as a thin sheet which breaks up into spray with the usual broad drop-size distribution (Dombrowski and Fraser, 1954). The drop size is readily varied by altering the speed of rotation of the disc. The method is thus particularly suitable for producing homogeneous mists."

"In order to attain the very high revolutionary speeds required to generate fine mists from a disc of reasonably small diameter, Walton and Prewett used a small, self-balancing top of the type developed by Henriot and Huguenard (1925), Beams (1937), and others. Driven by compressed air, these tops are capable of rotational speeds of several thousand revolutions per second, giving radial accelerations of the order of 10^6g. The liquid is fed from a fine tube on to the center of the rotor (See Figure 7), and spreads over it to the periphery as a thin film. The spray projected from the rotor always contains a number of

> fine satellite drops in addition to the main uniform drops. Owing to their smaller mass the satellite drops are projected a much smaller distance from the rotor than are the main drops, and by using an independent source of suction the satellite drops may be separated from the mist if their presence is undesirable."

Phillipson (39) developed an apparatus for the production of monodisperse particles which is based on the spinning disc principle. It has been tested in the production of polystyrene particles and it proved to be possible to make these with a standard deviation of 4% in diameter. The drop formation process at the edge of the disc has been photographed with a ruby laser technique. From the pictures, the formation of drops, satellite drops and double drops is discussed as well.

May (28) describes a generator in which operation stability is given to the air drive, air supported, high-speed spinning top spray device by including an oil damped flexible metal bellows as a stator mounting and by reducing sprung weight to a minimum. Uniforma drops ranged in size from 10 to 200 μ.

c. Ultrasonics

Topp (49) describes a photographic study of the mechanism of disintegration in ultrasonic atomization. In his article, existing theories to account for liquid disintegration in ultrasonic atomizers are reviewed and examined in the light of observations of two different 40 kHz atomizers. Photographic techniques including single exposure, high-speed still and synchronized flash high-speed cine photography were used. Corroborating evidence for a capillary wave mechanism was obtained but disintegration as a result of cavitation effect was also observed. Sonoluminescence and therefore cavitation was detected at all power levels capable of causing atomization. A mechanism for the cavitation effects is proposed. From this the performance of a typical atomizer is explained and the general conditions for obtaining a near monodisperse spray at optimum throughputs are given.

d. Other Atomization Techniques

Other atomization techniques developed more recently are as follows. Ström (46) describes the generation of monodisperse aerosols by means of a thin jet of liquid issuing from a nozzle at a high velocity which disintegrates spontaneously into droplets under the action of surface tension. A periodic disturbance of the jet can be used to control the disintegration so as to make all droplets of the same size. A system for generating monodisperse sprays according to the principle outlined above has been designed and built by Ström. The jet is modulated by axial vibration of the nozzle, which is mounted at the center of a membrane. The membrane is vibrated by means of electrostrictive elements. Droplets in the diameter range of 15–40 μ have been produced at a vibration frequence of 20–300 kHz. The stream of droplets has been analyzed in several ways. A jet of air perpendicular to the droplet stream has proved to be of special value. Several air jets, pulsed in suitable phase relations, are utilized to disperse the stream of droplets and to prevent the droplets from coalescing during the drying phase of the aerosol generation.

Roschke (42) describes the control and performance of a small oil-smoke generator for use in the 1.0 to 4.5 atm range and discusses the application to flow visualization. This generator does not seem to have good possibilities for LDV applications.

Dabora (9) describes a technique for producing momodisperse sprays which makes use of Rayleigh's criterion for the break up of capillary jets by mechanically vibrating a number of uniform size capillary needles arranged in parallel. It was used to produce sprays in the size range of 290 to 950 μ but in principle there seems to be no reason why this range cannot be extended claims Dabora. The regime of spray sized where drop coalescence is likely to take place is delineated, and methods of minimizing coalescence are also described.

Schneider and Hendricks (45) discuss a method useful in the production of streams of uniform-sized droplets, which are uniformly spaced relative to another. An extension of the method which is useful for the production of

single droplets of known size is also given. The method is based on the principle that a cylinder of liquid is dynamically unstable under the action of surface tension. A capillary wave is launched onto a cylinder of liquid or jet which selects a particular mode of instability. The process of the disintegration of the jet is thereby regularized to the extent that extremely uniform droplets result. The size of the droplets is controlled by the inside diameter of the capillary tube through which the liquid flows, and therefore, the size can be varied over wide limits. By charging individual droplets and using electrostatic means to deflect them out of the stream, individual droplets can be isolated.

2. Chemical Process and Combustion

a. Generation of Aerosols by Chemical Interaction in the Gas Phase.

According to the information supplied by Green and Lane the generation of aerosols by chemical interaction in the gas phase will not have good possibilities for LDV applications due to coagulation problems encountered. For example, the characteristics of an aerosol formed by chemical interaction differ according to the extent to which the gases are mixed before they react, and the extent to which coagulation is reduced by immediate dilution of the aerosol initially formed. For instance, when two reacting gases are simply brought into contact in a chamber, the reaction product is formed in the course of the irregular mixing process, and a heterogeneous rapidly coagulating aerosol results. However by very rapid mixing of the jets of air carrying the vapors of water and reactants, it is possible to produce particles which are much more uniform in size than those of aerosols generated by normal chemical interaction methods. However, due to the scale factors involved in designing an aerosol generator for a large wind tunnel, this generation technique would present tremendous difficulties in avoiding the coagulation problems.

The second major problem with chemical generation of aerosols is that the aerosols thus generated are highly toxic or corrosive. Some of the more common reactions are the production of NH_4Cl smoke from HCl and NH_3; or

H_2SO_4 mist from SO_3 and H_2O vapor. Such reactions are not permissible for LDV applications since approximately 10% of the air in the wind tunnel is exhausted with every cycle in the tunnel.

b. Aerosol Generation by Combustion

The mechanism involved in generating smokes by combustion is difficult to analyze due to the high temperatures involved and the rapidity of the reactions taking place. Combustion in a carrier gas is occasionally employed as a method of aerosol generation in the laboratory; highly dispersed ferric oxide aerosols, for example, are produced by burning, in air, a stream of carbon monoxide laden with iron pentacarbonyl vapor. On the large scale required in a wind tunnel, combustion is difficult to control and safety requirements are difficult to achieve.

3. Condensation and Nebulization

Tomaides, et. al. (48) have evaluated an improved version of the condensation aerosol generator for producing monodispersed aerosols, which had been previously described by Lui, Whitby and Yu. Its performance has been evaluated on four liquid aerosol materials: di-2-ethyl-hexyl phthalate, oleic acid, glycerin, dioctyl phthalate, (DOP), and two solid aerosol materials: stearic acid and triphenyl phosphate, (TPP), DOP and TPP have been found to give the most monodispersed aerosols with geometrical standard deviation ranging from 1.06 to 1.12. The number median diameter of the aerosol ranged from 0.9 to 1.1 μ, depending on the aerosol material used, and the output aerosol concentration was on the order of 10^6 particles per cm^3.

Nicolaon, et. al. (36) have developed a new liquid aerosol generator. In their first article they describe the generator as follows:

> "Helium, which serves as the carrier gas, picks up NaCl nuclei in a combustion furnace and then passes down a vertical tube along the sides of which is flowing a film of dibutyl phthalate (DBP) maintained at an elevated temperature. The aerosol is formed by condensation of DBP on the nuclei as the mixture is cooled upon leaving the tube.

> "This generator is capable of maintaining a stable output of aerosol over along period of time. Furthermore, after an extended shutdown, it will reproduce the same aerosol for the same operating conditions. The influence of the furnace temperature, DBP film temperature, flow rate, dilution of nuclei, and a number of other factors on the size distribution has been studied."

In a second article the effect of reheating and a description of studies on the condensation zone is given for this aerosol generator:

> "If the aerosol emanating from the generator . . . is reheated and subsequently condensed, an aerosol having a significantly narrower size distribution is formed. The stability and reproducibility of the earlier generator is maintained with this added regenerator."

> "Condensation occures in a paraboloidal-shaped isothermal region. Theoretical heat rransfer calculations agree with the temperature measurements and predict precisely the observed shape of the paraboloidal condensation zone. Theoretical estimates of the size of the nuclei have been made using values of the supersaturation in the condensation zone obtained from experiment. The radial variation of the size distribution of the aerosol as well as its continued growth downstream from the condensation zone has been measured."

> "The formation of the aerosol is primarily an equilibrium process. Growth is very rapid after the onset of nucleation."

May (29) describes a collision nebulizer which is widely used to produce fine aerosols from a liquid supply. Details of its design and operating characteristics are given, including air and liquid consumption, aerosol output rate and droplet size distribution (approximately 0.25 to 30 μ). An adaptor for the outlet of the nebulizer is also described. This is used when monodispersed aerosols are being generated and enables the output of particles to be increased.

4. Specialized Techniques

A number of specialized techniques of aerosol generation are described below. These are mainly applications to one particular aerosol material or one highly limited technique requiring very special equipment.

Kanapilly, et. al. (25) describe a new method for the controlled generation of spherical aerosol particles of insoluble metal oxides. The method consists of (a) nebulizing a solution (or suspension) of the chosen metal in chelated or other form, (b) drying the droplets, (c) passing the aerosol through a high temperature heating column to produce the spherical oxide particle, and (d) colliding the aerosol with the addition of diluting air. The procedure provides a continuous source of insoluble aerosols suitable for animal inhalation exposure or other experimental uses. The size distribution of an aerosol produced by this method depends upon the distribution of the nebulized droplets but the mean diameter ranges around 5.8 µ. This technique has been used with a Fulwyler Droplet Generator to produce monodispersed aerosols. The physical and chemical nature of aerosols of zirconium and lanthanum compounds generated by this method were studied. Physical characteristics were ascertained by electron-microscopic observations, particle density measurements, and instrumental techniques.

Hendricks and Babil (18) describe a method for the generation of large quantities of uniform solid particles of 0.5 to 10 µ radius. The particles are produced by the evaporation of solvent content of the liquid droplets of the solution sprayed in the air and driven down a high temperature evaporation column. The gneration of drops is accomplished by so-called Rayleigh method, i.e., by the electromechanical excitation of unstable capillary waves on the surfaces of the liquid jets issuing from capillary tubes, resulting in the break up of jets into uniform drops. This method allows the routine generation of drops of 10 to 300 µ radius at rates up to 4×10^5 drops/sec/capillary. The particles obtained from evaporation of drops are spherically shaped polycrystalline structures of the solute material. The size of the particles correspond to the initial concentration of solute in the solution droplets, implying near complete evaporation of the solvent constituient. A theoretical explanation is made of the evaporation process and subsequent solute recovery.

Hendricks and Tsui (17) describe the production of uniform droplets by means of an ion drag pump. An ion drag pump generates a low pressure, and when it is excited by an ac voltage, it can be made to produce a periodic

pressure of rather high frequency, when compared with mechanical pumps. The pump can be used to break a cylindrical liquid jet into uniform droplets by launching a wave on the liquid jet. The sizes of the droplets depend on the jet diameter and the frequency of pressure variations. In an experimental system the supply voltage to the pump was varied from 175 to 2000 volts, and a step-up transformer was used to raise the low voltage oscillator output to the high voltage necessary for pum operation. From the relation between the frequency of applied voltage and the frequency of the pressure generated, it was found that the pressure was proportional to the square of the applied voltage. The method described has been used with multiorifice systems to produce multiple streams of synchronized droplets.

Grider, et. al. (8) describe the operating parameters and the performance characteristics for a dry-powder Fe_2O_3 aerosol dispersing device with long-time output stability. Wolf (53) describes the production of uniformly sized droplets of pure liquids, solution, suspensions, and of solid particles in the size range of 4 to 200 μ in diameter employing the vibrating reed. Salient features of the various devices are discussed where particular attention is devoted to the stability in size and uniformity of the droplets or particles produced and their mechanism of formation. The methods described have found application in a variety of fundamental investigations, such as droplet evaporation and plant growth regulator studies, but their inherent low capacity makes them less suited for large-volume aerosols or sprays as are encountered, for example in spray drying or wind tunnel applications.

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Chemical Abstracts 1972-1974

Engineering Index 1968-1974

I & E C 1966-1970 (also I&EC Prod. Res. & Dev.; I&EC Fundamentals)

International Aerospace Abstracts

J. of Aerosol Science 1970-1973

J. of Sci. Instrum. (J. of Physics E) 1964-1972

Monthly Catalog of U. S. Gov't Publications 1968-1972

Physics Abstracts 1971-1972

Rev. of Sci. Instrum. 1960-1972

STARS 1970-1973

5. Summary of Results Applicable to Project Needs

Measurement of Particle Characteristics

Most applicable to our project is particle size estimation directly from the modulated signal outputted onto the oscilloscope. By using equation (4) the fringe spacing ΔX may be obtained. Then the quality of the signal would give a very good first order approximation to the particle size.

Other particle properties, such as particle mass or specific gravity, could be investigated according to some variation of techniques found in the literature. For example, the principle of Chuan's active impactor (7) may be utilized for particulate mass determinations.

Aerosol Material

Of first interest would be the #5 wt mineral oil currently being used by Dr. Orloff at NASA Ames. Other weights of oil may be examined to determine the relative merits of the oils.

Polyotyrene and latex spheres should also be considered. These are produced by Dow Chemical Co. Polyotyrene is cheaper than latex. In either case, these spherical solid particles can be collected as the air is being exhausted from the tunnel, and reused.

Generation Techniques

Of primary interest for consideration is using the air blast atomizer principle as outlined by Melling and Whitelaw. (See pp. 15 to 16.) A prototype can be constructed and tested in the laboratory. The scale factor problems must also be considered to determine whether a scaled-up version of the prototype, or some modification thereof, is capable of producing the large quantities of aerosol needed in the 7' x 10' wind tunnel.

Another technique which seems to have good possibilities is that of ultrasonic atomization. However, more literature research needs to be done on this technique prior to attempting an implementation of it in the laboratory.

Since we are considering working with large volumes of air, the spinning disc technique and the generation of aerosols by chemical and combustion processes seem impractical. In the spinning disc technique, the uniformity of particle size deteriorates rapidly as volume of material is increased. The reactions in the chemical and combustion processes are difficult to control, or produce toxic products and by-products. As a consequence, these methods are not recommended at the present time.

The limiting factor in condensation and nebulization techniques seems to be the composition of the nuclei upon which the aerosol material is to be condensed. These nuclei are usually salt nuclei which would have very corrosive effects upon the wind tunnel. If any other type of condensation nuclei can be found, this technique may, upon further investigation, prove useful.

III. SUMMARY OF COMMERCIALLY AVAILABLE AEROSOLS AND AEROSOL GENERATORS

This section summarizes the results of investigating the commercially available products which may be of use to our project. It is possible that some of these references will have information that is useful later on, but, at present, we found nothing which we can apply immediately to our project.

We reviewed the following:

1) Chemical Engineering Catalog
2) OEM Product Encyclopedia (1970)
3) Thomas Register of American Manufacturers 1971 (Thomas Publishing Co., 461 Eighth Avenue, New York, New York 10001)

We summarize our results (following each of the references) by subject matter.

A. CHEMICAL ENGINEERING CATALOG

Spray & Atomizing Nozzles

Schutte and Koerting Company
Cornwells Heights, Pennsylvania 19020
(215) 639-0900
- - - - - "ask for Bulletin #6A"

B. OEM PRODUCT ENCYCLOPEDIA (1970)

Ultrasonic Fog Generator

Thomas J. Scarpa, President
Edison Instruments, Inc.
54 West Cherry Street
Rahway, New Jersey 07065
(201) 381-0140

Nebulization rate - - - .5 to 10 cc/min
Droplet size- - - - - - 1 to 5μ
Air Flow rate - - - - - less than 1 to 30 liters/min
Price: $495.00

C. THOMAS REGISTER OF AMERICAN MANUFACTURERS (1971)

Generators: Aerosol

Aotek-Fritzsching, Inc.
P. O. Box 7440T
Rochester, New York 14615
(716) 254-6870
- - - - - Precision Electronic Instruments for Research, Industry, and Medicine.

Edison Instruments Inc.
46 Liberty
Metuchen, New Jersey 08840
(201) 549-4260

Schoeffel Instrument Corp.
24-T Booker Street
Westwood, New Jersey 07675

Sonic Development Corporation of America
260 Hawthorne Avenue
Yonkers, New York 10705
(914) 968-3838
- - - - - Atomizers, Spraying Devices, etc.

THOMAS REGISTER (con't)

Generators: Smoke & Gas

Superior Signal Company, Inc.
W. Greystone Rd., Dept. T
Spotswood, New Jersey 08884
(201) 257-0600
- - - - - Manufacturers of Smoke Generating Products.

Testing Machines, Inc.
398 Bayview Avenue
Amityville, L. I., New York 11701
(516) 598-1400
- - - - - Testing Machines of All Types for All Industries.

Nebulizers

Bio-Logics Inc.
1 Research Road at Stadium
Salt Lake City, Utah 84112
(801) 521-6195
- - - - - Laboratory Apparatus; Vortex, Gas, & Ultrasonics.

Universal Ultrasonics Inc.
99 Lamar Street
West Babylon, New York 11704
(516) 643-7535
- - - - - Ultrasonic Equipment for Aerosol Applications.

Nozzles: Spray Atomizing

Monarch Mfg. Works, Inc.
2505 East Ontario Street
Philidelphia, Pennsylvania 19134
(215) 739-2809

Spraying Systems Co.
3223 Randolf Street
Bellwood, Illinois 60104
- - - - - Spray Nozzles and Accessories for Every Chemical and General Industry Application.

THOMAS REGISTER (con't)

Sprayers: Chemical

Lonn Mfg. Co., Inc.
2021 West 18th Street
Indianapolis, Indiana 46207
(317) 639-5517
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IV. EXPERIMENTAL CAPABILITY

A. BACKGROUND

Laser Doppler Velocimetry involves the indirect measurement of the velocity of an air flow. The method actually measures the velocity of particles traveling in the air stream. Ideally, the particles in the air faithfully follow the motion of the air. If the particle is small and light enough, this condition is closely met.

In the experimental set-up a laser beam is split and then focused to create an interference pattern at the point where the airspeed is desired. See Figure 8. The light waves constructively and destructively interfere so as to create a region of evenly spaced light and dark bands. As a particle passes through the laser beam intersection, it reflects the laser light in alternate light and dark fringes, thus producing a modulated light signal. This signal can be collected by a lens and focused into a photomultiplier tube, yielding a modulated electrical signal which can be displayed on an oscilloscope.

From the signal on the oscilloscope, a number of particle characteristics can be determined. A rough estimate as to the particle size can be made, since a particle of size on the order of the fringe spacings will give a well defined signal, whereas a larger particle will yield a signal that is not well resolved. Since the wavelength of the laser ligth is known, the fringe spacing can be calculated and thus the component of velocity of the particle perpendicular to the fringe pattern orientation can be determined.

B. EXPERIMENTAL RESULTS TO DATE

A simplified version of the velocimetry equipment at NASA Ames was constructed to make possible simple measurements of the characteristics of any particles that would be produced.

A listing of the equipment is as follows:

Spectra Physics Laser, Model 155
IF High Voltage DC supply (NASA Ames)
ACTION Lab Amplifier (X10, X100, X1000)
Photomultiplier tube (NASA Ames)
Hewlett-Packard 130C oscilloscope
Beam Splitter (NASA Ames)
Optical Bench, lens holders, assorted lenses (converging lenses)
Wooden wind tunnel, 6' long with test section 6" x 6" x 6"
Rotating lucite disc with motor

The above equipment was arranged and aligned with the help of Dr. K. L. Orloff as shown in Figure 9. The HP 130C oscilloscope was replaced by a Tectronix 516 since the 130C did not have the necessary frequency response. The desired modulated signal was obtained with cigarette smoke and with smoke produced by dripping droplets of #5 wt mineral oil on a hot soldering iron. However, there was the problem of stray triggering of the oscilloscope sweep, thus yielding a messy signal.

A Kronhite band pass filter Model 330M was obtained to clean up the photo-signal. Unfortunately, the frequency response of this filter only

went up to 20 kHz whereas the expected range of the modulated signal was on the order of 1MHz.

The equipment was then set up to focus within the model wind tunnel. On axis forward scattering was tried as shown diagrammatically in Figure 10. Unfortunately, the laser beams would also be directed into the photomultiplier tube which would cause the tube to operate in a range where it could not pick up any signal caused by reflections off of the micron sized particles. Attempts were made to block out the beams with opaque tape placed on the collector lens appropriately. Since we could not find an adequate lens which would not need blocking of the beams, and since the beams could not be blocked off entirely, we moved the phototube and collector lens to the off-axis configuration where an acceptable signal level (approx. 2-3 m-amps) could be achieved.

Dr. Orloff visited us on the 18th of May. A Tektronix Model 465 oscilloscope was used at that time, as well as a Kronhite band-pass filter which Dr. Orloff brought for the project laboratory. Dr. Orloff was able to get a modulated signal using smoke produced by dropping oil on a soldering iron and by using the irregularities on the spinning lucite disc.

For some unknown reason, the signal was no longer observable after Dr. Orloff's visit. A lot of "noise" was being picked up around the 0.5 MHz range. Investigation showed that the filter itself was supplying the noise. With the oscilloscope connected directly to the filter, and with no input to the filter, the "noise" of 0.5 MHz was obtained.

The lab work has been conducted in a room shared with a Nuclear Magnetic Resonance machine for want of another room that could be kept locked and that had a window or flue through which may smoke produced could be dispelled. Dr. G. R. Van Hecke, Chemistry Professor, HMC, said that the NMR, which runs continuously and operates around a range of 50-60 MHZ, could be emitting "noise" at 0.5 MHz. Since the NMR was being used for research and could not be turned off, we were not able to verify the NMR as being the source of the "noise".

This project most likely will have to move to another room. If further work is to be done, it is highly recommended that the project be

relocated. If no other rooms with windows on vents are available, a system of baffles and/or collectors will have to be designed, bought or built to collect any aerosols produced.

For the control signal produced by the rotating lucite disc it is suggested that a diffraction grating be found with spacings on the order of the fringe spacings and mounting it on a rotating disc. This may result with an in-phase reflected signal which can be used to calibrate the equipment and as a source of a reference signal for particle size measurements.

Once a control signal is obtained, recording it and any other signals using a Poloroid CR-9 Land Oscilloscope camera is possible. This will afford an easy comparison method by which the characteristics of various aerosol materials may be judged.

C. LAST MINUTE RESULTS

A very recent visit on May 31, from Dr. Orloff resulted in our being able to recover our signal. The signal was obtainable both from the rotating lucite disc and from oil particles generated by dropping the oil on the soldering iron. Dr. Orloff also showed us how best to photograph the signal.

Subsequent work showed the oil particle size to be very sensitive to the temperature of the soldering iron. When the temperature gets too high, very many particles much smaller than the fringe spacing are produced which give a very "noisy" type of signal. If the iron is not hot enough, no smoke is produced. For future work it is suggested that the optimum temperature vs. particle size range be determined. This can be accomplished by thermocoupling the heat source of the oil smoke and obtaining a gage which read out temperature directly, or utilizing conversion tables for converting millianspere output to temperature in °C. Such thermocouples and gages are obtainable through Mr. Earl Thornton of HMC chemistry department stockroom.

Preliminary photographs of the signals showed the importance of having a continuous supply of uniformly sized and distributed particles. For future work a more reliable and controllable oil particle production by heating method needs to be designed. This could easily be done by using a thermocoupled heat source and a continuous oil supply.

V. CONCLUSIONS

A. LITERATURE SEARCH

This semester's work has resulted in a comprehensive literature survey, the results of which are summarized very briefly as follows:

The following basic topics were investigated:

Aerosols
Air Pollution - analysis
Atomizers
Dispersion
Particles - optics
- size analysis
Smoke - generators
- density measurements
Sprays
Wind Tunnels - visualization

Directly applicable to our project are the following results.

Measurement of Particle Characteristics

Most adoptable to our project is particle size estimation directly from the signal trace output of the oscilloscope. By using the following equation the fringe spacing ΔX may be obtained.

$$\Delta X = \frac{\lambda}{2 \sin \phi} \qquad (4)$$

where λ is wavelength of light beams intersecting at an angle 2ϕ. The quality of the signal can then be used to obtain a good first order approximation to the particle size.

Other particle properties, such as scattering properties, particle mass or specific gravity, could be investigated according to some variation of the techniques found in the literature. For example, the principle of Chuan's active impactor (7) may be utilized for particulate mass determinations. However, such investigations will be appropriate more for the

later stages of the project.

Aerosol Material

Of first interest would be the #5wt mineral oil currently being used by Dr. Orloff at NASA Ames Research Center. Other weights of oil may also be examined to determine the relative merits of the oils.

Polystyrene and latex spheres should also be considered. These are produced by Dow Chemical Co. Polystyrene is cheaper than latex. In either case, these spherical solid particles can be collected as the air is being exhausted from the tunnel, and then reused.

Generation Techniques

Of primary interest for our consideration is using the air blast atomizer principle as outlined by Melling and Whitelaw. The atomizer they constructed uses silicone oil and is described in Section 2.III.A.1. Figures 5 and 6 illustrate the air blast atomizers. A prototype can be designed, constructed, and tested in our laboratory. The scale factor problems must also be considered to determine whether a scaled-up version of the prototype, or some modification thereof, is capable of producing the large quantities of aerosol needed in teh 7' x 10' wind tunnel at Ames.

Another technique which seems to have good possibilities is that of ultrasonic atomization. However, more literature research needs to be done on this technique prior to attempting an implementation of it in the laboratory.

Since we are considering working with large volumes of air, other aerosol generation technqiues have been found to be impractical for laser Doppler velocimetry applications. In large output volumes, the size distribution of particles generated by the spinning disc technique is non-uniform and the ranges are too large for LDV. The large scale reactions involved in chemical and combustion processes are difficult to control. Finally, the limiting factor in condensation and nebulization techniques

seems to be the composition of the nuclei upon which the aerosol material is to be condensed. These nuclei are usually salt nuclei which would have very corrosive effects on the wind tunnel.

B. COMMERCIALLY AVAILABLE PRODUCTS

Upon completion of the literature survey, we investigated the commerically available products which may be of use to our project. We found a limited number of references in the Chemical Engineering Catalog, OPH Product Encyclopedia (1970), and the Thomas Register of American Manufacturers (1971). Some of these references may be useful in later stages of the project, but at present are not immediately applicable to our needs.

C. LABORATORY WORK

Concurrent with our literature survey and our investigation of commercially available products, we developed an experimental capability. This capability is primarily aimed at obtaining a first order approximation to particle size distributions of various aerosol materials.

Figure 10 shows a schematic diagram of our most recent experimental apparatus. In three visits to Harvey Mudd College, Dr. Orloff helped us align our equipment properly and showed us how to obtain a good quality signal. At first we had difficulties obtaining equipment which would operated at the frequency range in which we were interested. After borrowing a filter from NASA and finding an oscilloscope both of which and frequency responses into the Mega Hertz range, we were able to process our signal.

A major portion of the semester was then spent trying to recover the signal as well as trying to eliminate some random "noise" at about 0.5 MHz, which was triggering the oscilloscope. The "noise" seemed to be produced by a Nuclear Magnetic Resonance Machine which is located in the same laboratory as our project. Since the NMR was being used continuously for research and could not be turned off, we were not able to verify the NMR as being the source of "noise". If the "noise" continues to present a problem in our experimental work, the project may be forced to be relocated an another laboratory.

Dr. Orloff's most recent visit resulted in recovery of our signal. Subsequent investigation showed the #5wt mineral oil particle size to be very sensitive to the temperature at which it was being produced. The temperature range at which optimum sized particles for LDV applications has not yet been determined but is planned for future work.

Preliminary photographs of the signals showed the importance of having a continuous supply of uniformly sized and distributed particles. If the temperature at which the oil smoke was produced got too high, many particles which were too small for LDV analysis were produced. These small particles, compounded with the intermittant oil smoke supply, produced a very "noisy" type signal which does not lend itself well to particle size analysis by laser methods. If production of an oil aerosol by heating an oil supply is to be reliably compared with the air blast atomization technique of producing an oil aerosol, a more continuous supply of uniformly sized oil particles is needed than simply dropping oil onto a soldering iron. This is the method we are using at present.

The development of a basic experimental capability puts us into a position of being able to analyze particle size distributions of various aerosol materials in detail. Suggestions for future work as a result of work done to date are given in detail in the next section.

VI. SUGGESTIONS FOR FUTURE WORK

As a consequence of the information on particles and aerosol generation techniques gained through the literature survey and of the successful development of a preliminary experimental capability, our suggestions for a second semester's work are as follows:

A. Develop a full experimental capability. This includes relocating the project if the "noise" obtained from the NMR continues to be a problem, and developing photographic techniques for easy recording of signals. At this stage, the photographs seem to offer the best records of our signals, from which our analyses can be made. We

also propose to design a continuous source of oil smoke produced by heating an oil supply. Finally, it is suggested that a control signal be developed. Mounting a diffration grating with spacings on the order of the fringe spacings on a rotating disc may result with an in-phase reflected signal which can be used as a reference signal for particle size measurements.

B. Examine the aerosol materials suggested in Section II. This includes various weights of mineral oils as well as polystyrene and latex spheres. Careful attention will be given to the cost of aerosol materials and the rates of consumption when used on the large scale needed for a 7' x 10' wind tunnel.

C. Design, construct, and test a prototype generator based on the air blast atomization principle as outlined by Melling and Whitelaw. Modifications resulting from preliminary testing should be investigated and evaluated. Problems involved in scaling the prototype up to a wind tunnel production model should be thoroughly considered and evaluated. If the results prove positive, a full scale wind tunnel aerosol generator should be designed. If negative, a new lab prototype should be investigated according to above procedure.

D. Research further possibilities in ultrasonic atomization techniques.

E. Report results to client.

Since we have completed the literature research and have developed a preliminary experimental capability needed for designing a monodispersed aerosol generator, and since we have a full schedule of work and research suggested for the future, we propose that this project be continued for the fall semester of 1974.

FIGURES AND TABLES

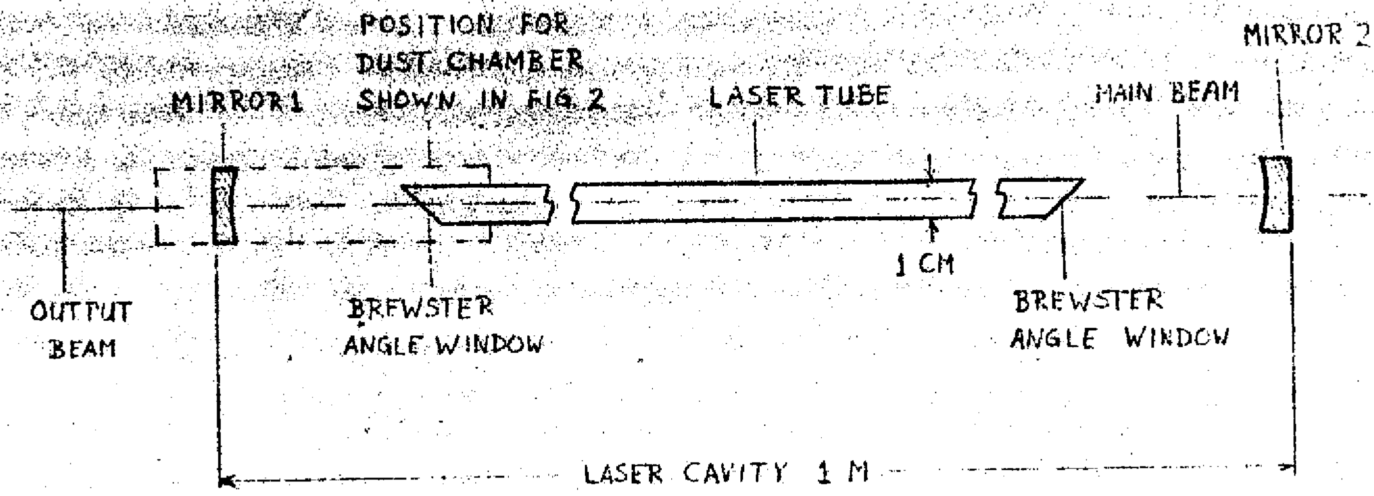

FIGURE 1. CONTINUOUS - WAVE GAS LASER

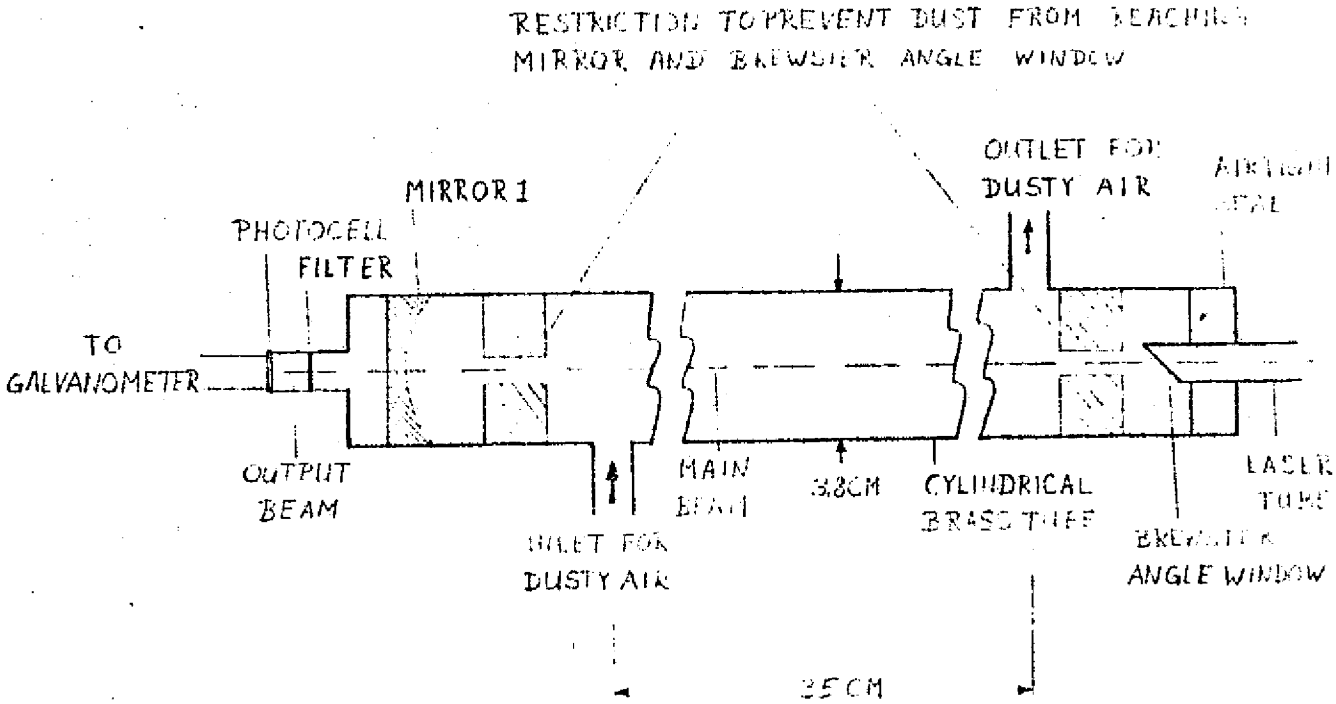

FIGURE 2. DUST CHAMBER WHICH WAS ADDED TO THE LASER

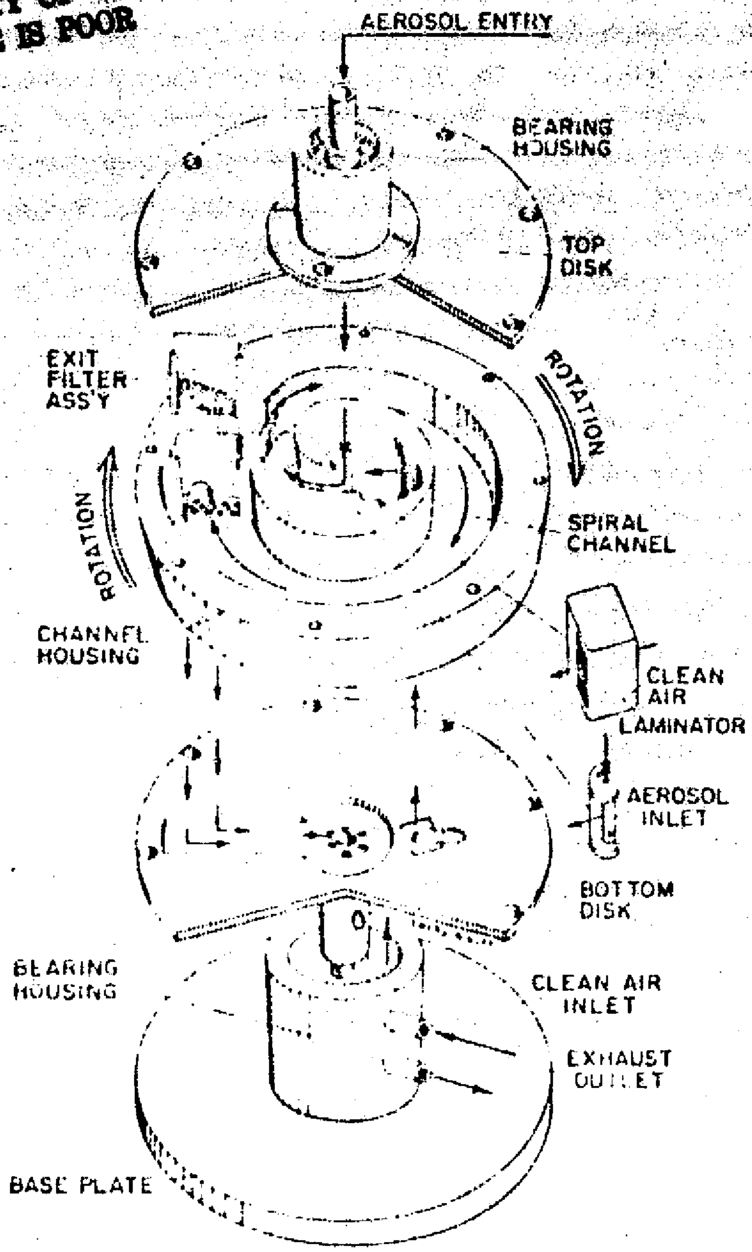

Figure 3. Exploded view of the Lovelace aerosol particle separator.

Approx. scale: diameter of disk = 17.8cm.

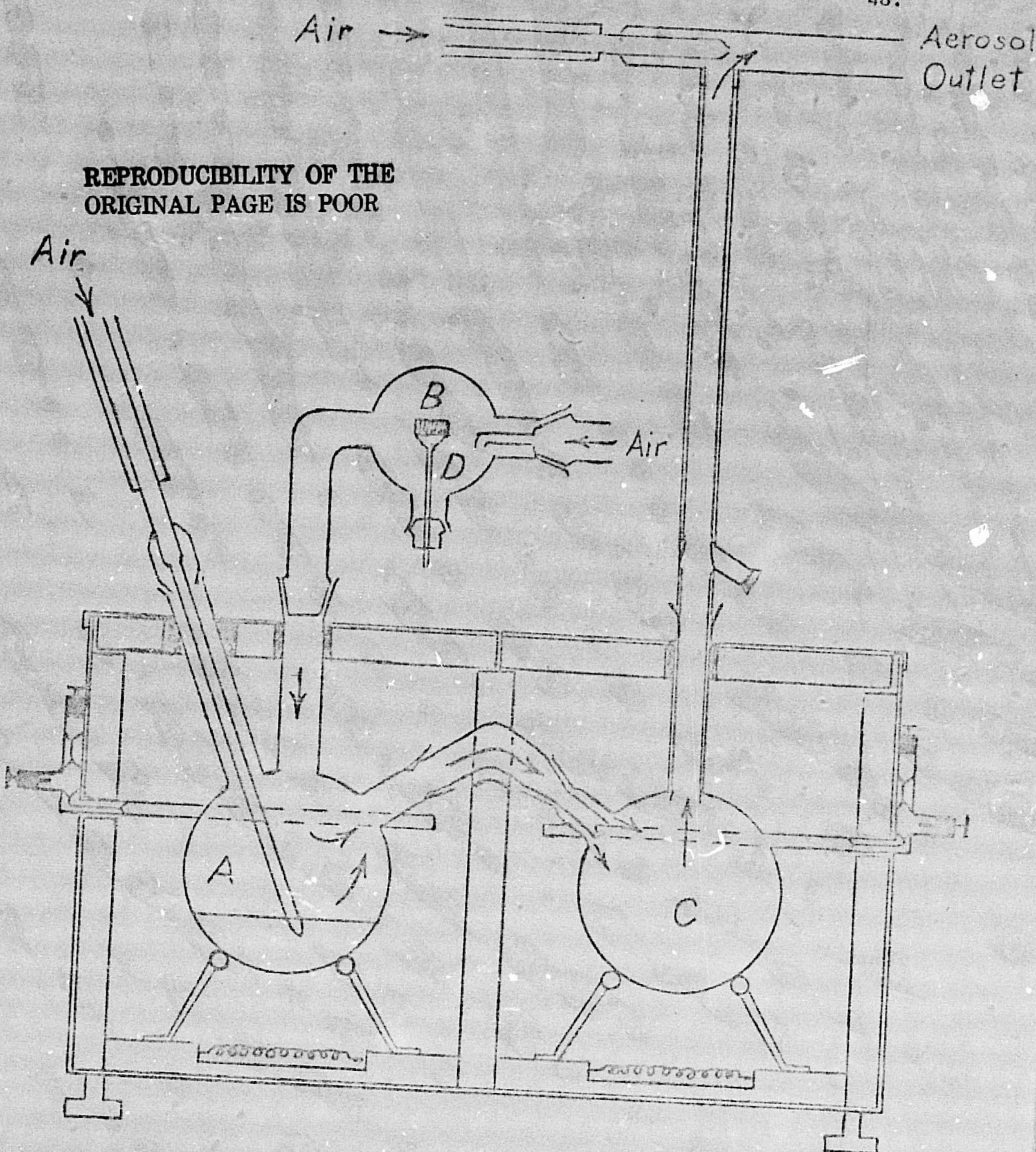

FIGURE 4. MONODISPERSE AEROSOL GENERATOR
(after Sinclair and La Mer, 1949)
A - GAS BOILER, B - CHAMBER,
C - REHEATER FLASK,
D - NUCLEI SUPPLY SPIRAL.

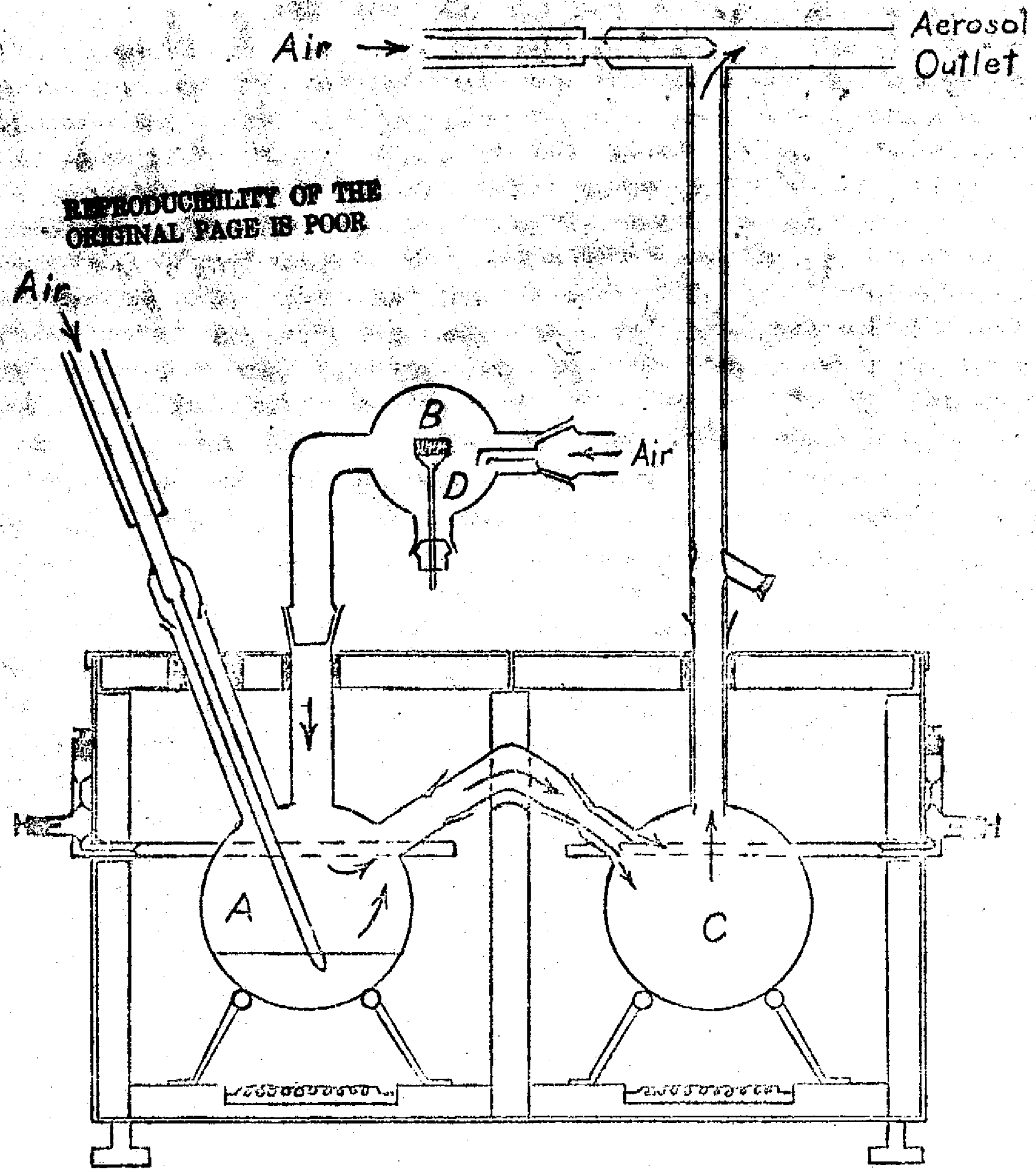

FIGURE 4. MONODISPERSE AEROSOL GENERATOR

(after Sinclair and La Mer, 1949)

A - GAS BOILER, B - CHAMBER,
C - REHEATER FLASK,
D - NUCLEI SUPPLY SPIRAL.

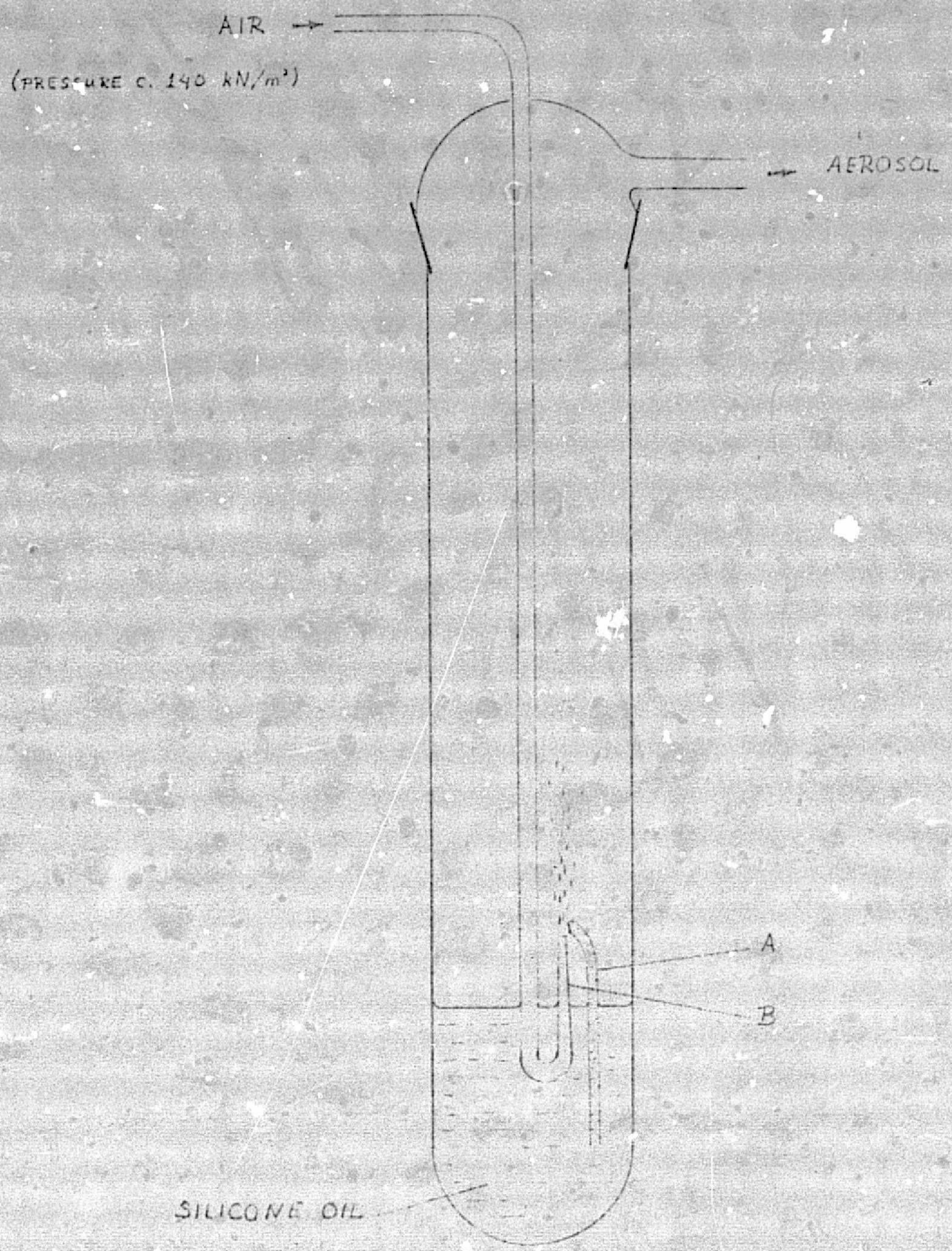

FIGURE 5. SILICONE OIL ATOMIZER

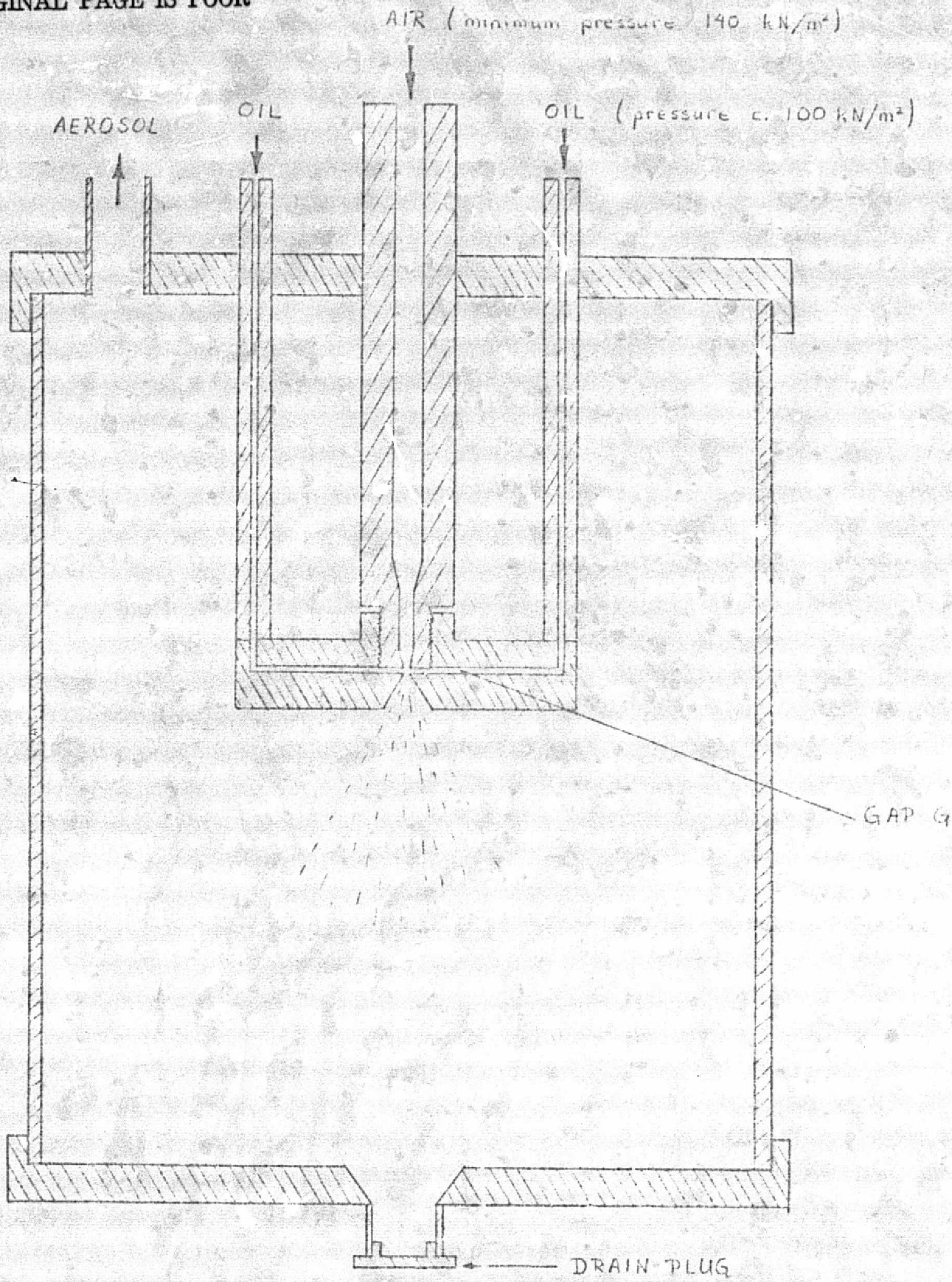

FIGURE 6. TWIN-FLUID ATOMIZER

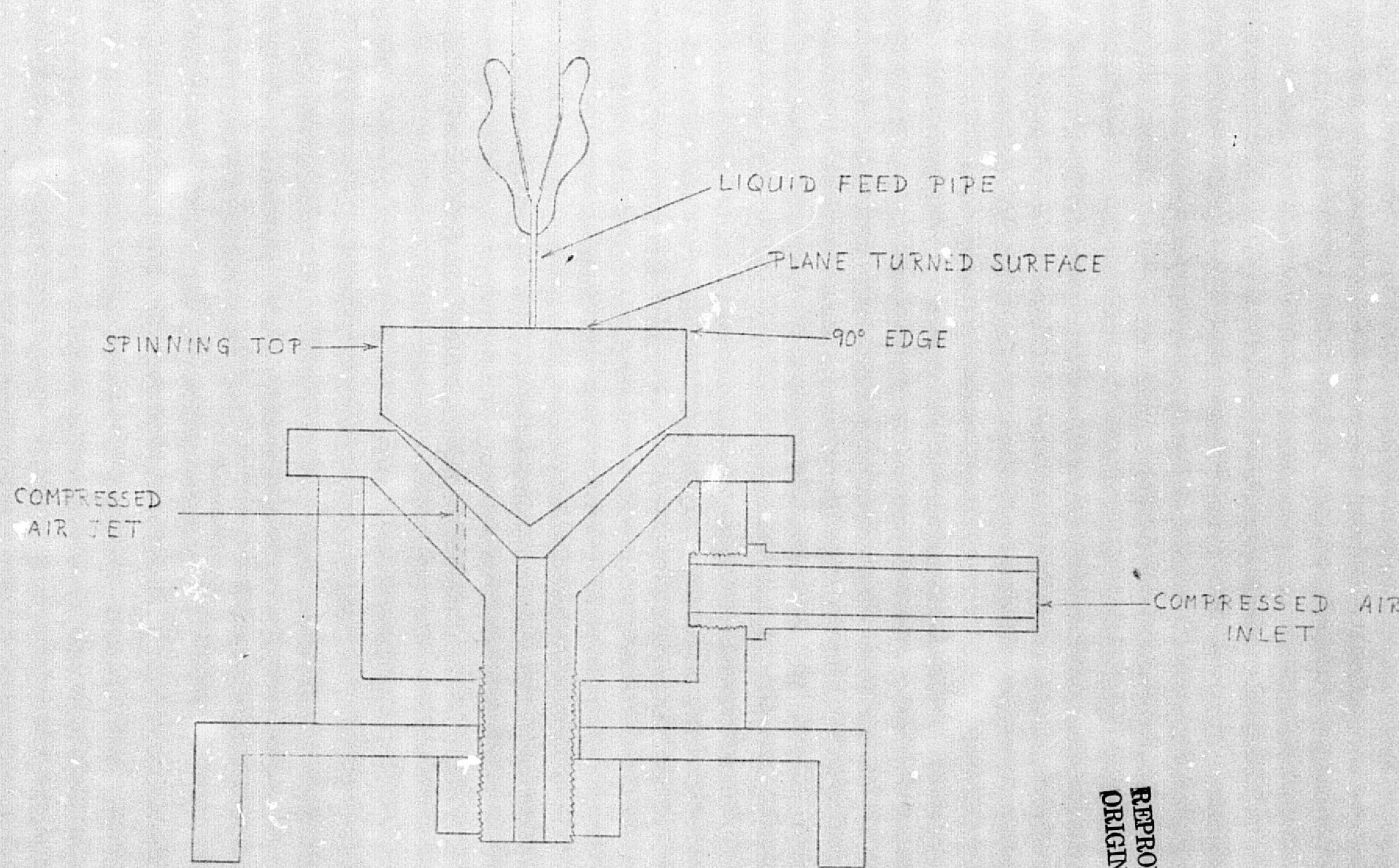

Figure 7. Spinning top atomizer (Diagrammatic)

(Walton and Prewett, 1949)

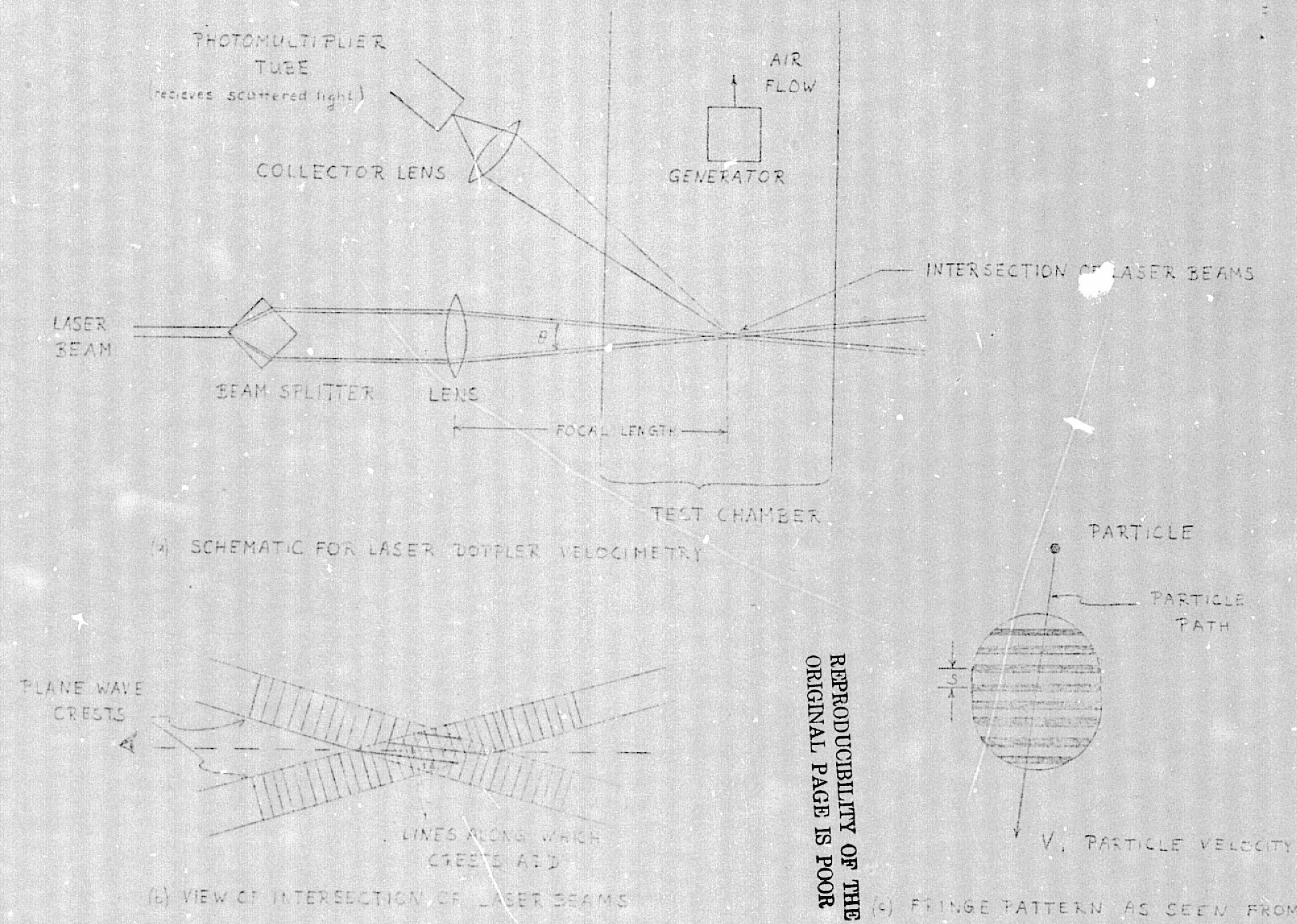

Figure 8. Schematics of Laser Doppler Velocimetry

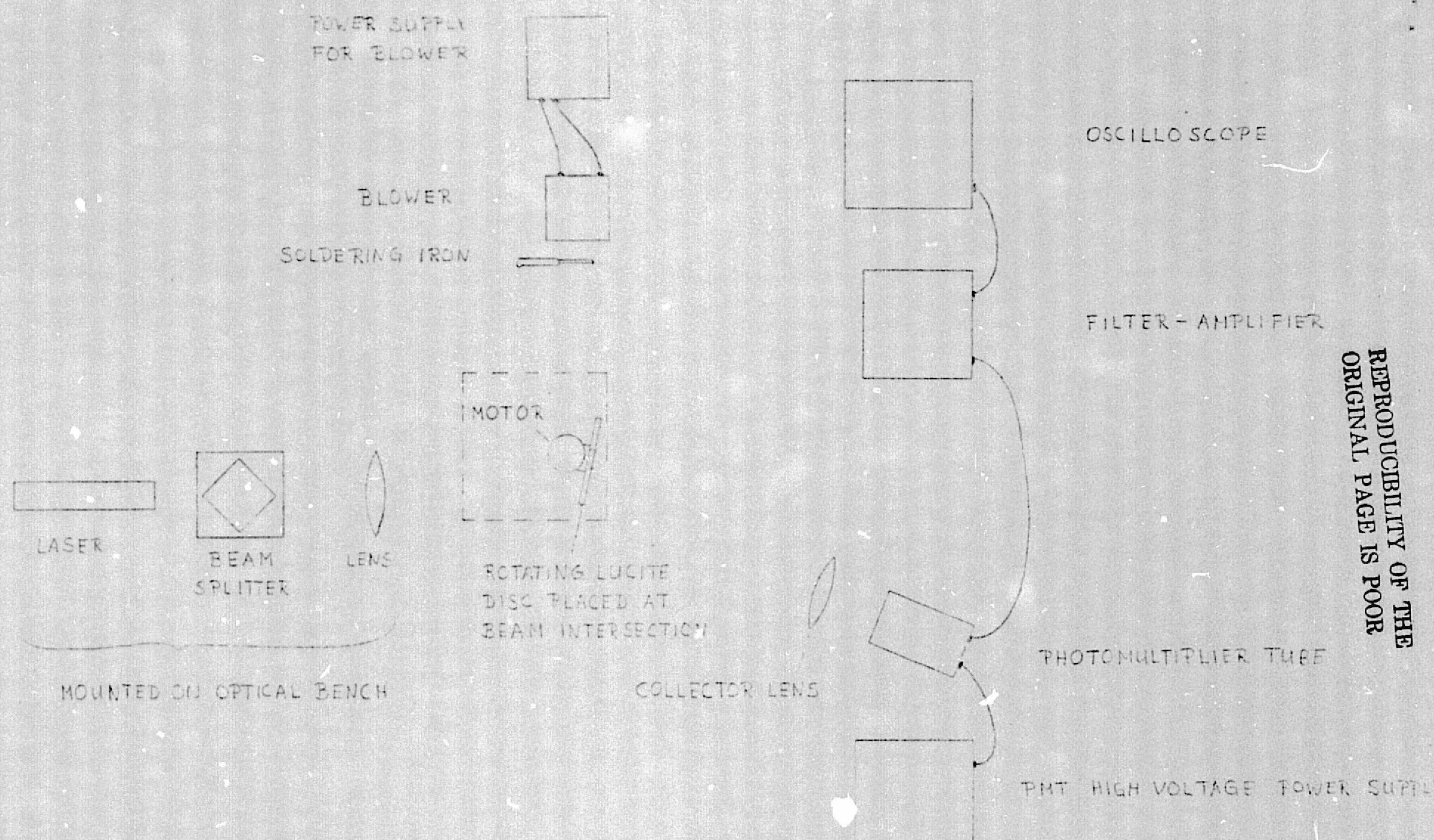

FIGURE 9. SCHEMATIC OF PRELIMINARY EXPERIMENTAL APPARATUS

NOTE: ROTATING DISC AND MOTOR CAN BE REMOVED TO ALLOW PARTICLES PRODUCED BY SOLDERING IRON TO BE BLOWN ACROSS BEAM INTERSECTION.

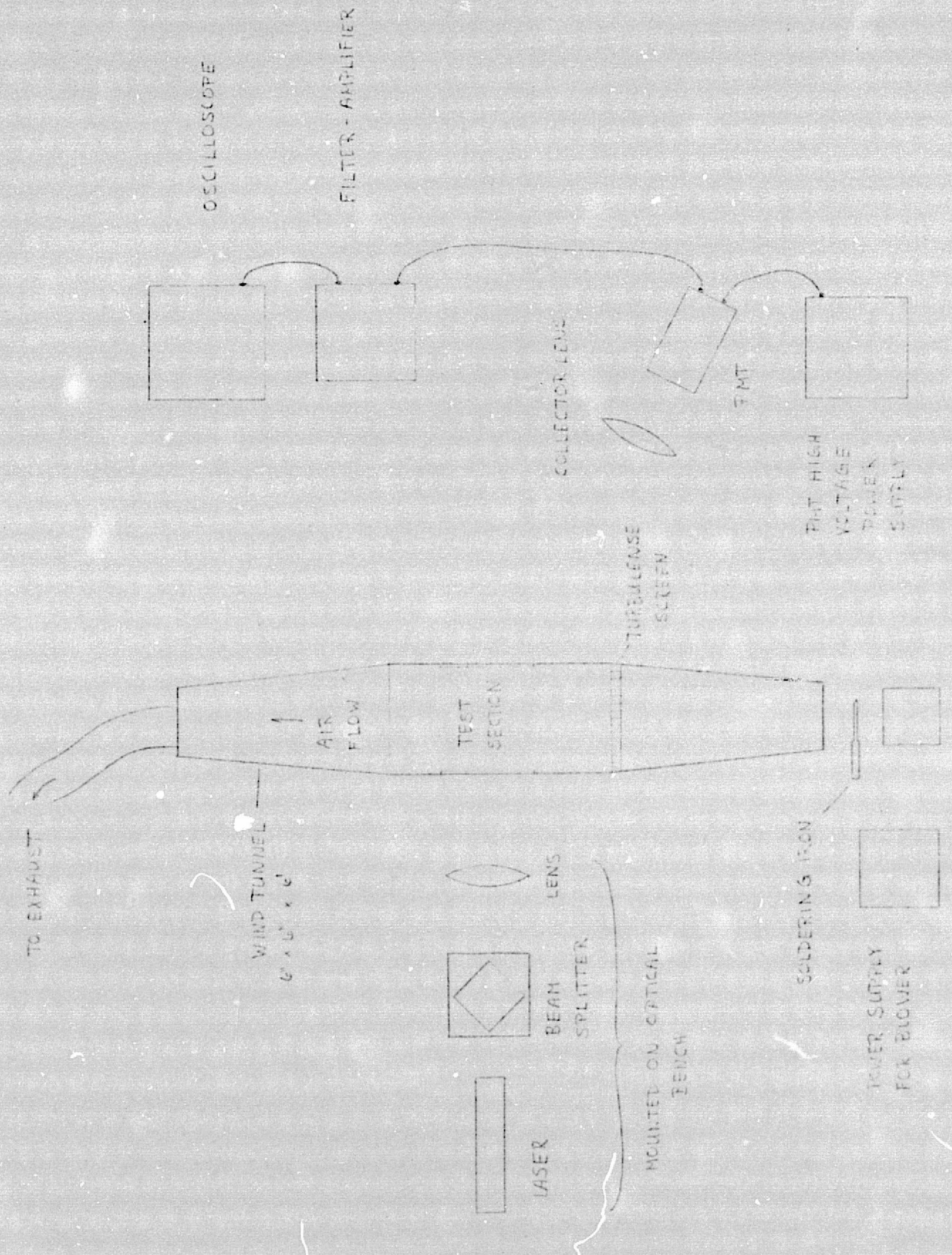

FIGURE 10. EXPERIMENTAL APPARATUS WITH WIND TUNNEL (DEA-PXS CONFIGURATION)

TABLE I. SIZE RANGES OF VARIOUS MATERIALS[1]

Item	Approximate Diameter in Microns (1 micron, μ = 10⁻⁶ m)		
Range of normal contaminants in quiet outdoor air	0.01	-	1.0
Range of temporary contaminants in outdoor air	1.0	-	100
Fog droplets	5.0	-	50
Mist	50	-	100
Drizzle	100	-	400
Rain	400	-	5,000
Metallurgical dust and fumes	0.001	-	100
Cement dust	3.0	-	90
Tobacco smoke	0.2	-	
Sulfuric acid mist	0.5	-	15
Limit of visibility with naked eye:			
absolute limit	10		
probable limit	40		
Diameter of large molecules	0.005		
Wave length of visible spectrum:			
violet light	0.4		
red light	0.7		
Diameter of human hair	50	-	200

1. Taft, Robert A., Atmospheric and Surface Sampling, U.S. Dept. of H.E.W.

TABLE 2. AEROSOLS USED IN LASER DOPPLER ANEMOMETRY[2]

Method of generation	Material	Quoted Diameter (μ)	Comments	Reference
atomisation	water	1–2	evaporation inhibitor added	(54)
	DOP	0.35–1.2	commercial atomiser used	(22)
	Teflon dust	75% less than 2	atomised from Teflon-Freon suspension	(41)
	silicone oil	mostly less than 5	very satisfactory	(31)
fluidisation	titanium dioxide	0.5–2	stable in flames up to 2500°C	(55)
	geon (PVC)	0.3–0.8	large agglomerates formed; erratic flow	
	aluminium, aluminium oxide	up to 8	in solid fuel rocket exhaust, and from fluidised bed in cold flow	(34)
chemical reaction	ammonium chloride	1.2	produced from ammonia and hydrogen chloride gases, (which are toxic and corrosive)	(22)
	stannic chloride		used in flames, but particles consumed	
combustion	tobacco smoke	0.1–1.0	dirty, unsteady flow	(31)
	magnesium oxide		from burning of magnesium powder; used in flames	(55)
	smoke bombs	over 3	corrosive, toxic, uncontrollable production rate	(41)
	smoke pellets	0.03–1.0	commercial product, low flow rate	
sublimation	ice	0.5	formed during expansion of humid air through supersonic nozzle	(24)

2 Melling and Whitelaw, "Seeding of Gas Flows for Laser Anemometry", DISA Information, No. 15, Oct. 1973